DISCLAIMER

The Advantages of Highly Controlled Lighting for Offices and Commercial Buildings

Francis Rubinstein and Dmitriy Bolotov, Lawrence Berkeley National Laboratory
Mark Levi and Kevin Powell, U.S. General Services Administration
Peter Schwartz, Peter Schwartz, & Associates, LLC

ABSTRACT

The paper presents results from pilot studies of new "workstation-specific" luminaires that are designed to provide highly, efficient, customized lighting for open-office cubicles. Workstation specific luminaires have the following characteristics: 1) they provide separate, dimming control of the cubicle's "ambient" and "task" lighting components, 2) occupancy sensors and control photosensors are integrated into the fixture's design and operation, 3) luminaires can be networked using physical cabling, microcontrollers and a PC running control software.

The energy savings, demand response capabilities and quality of light from the two WS luminaires were evaluated and compared to the performance of a static, low-ambient lighting system that is uncontrolled. Initial results from weeks of operation provide strong indication that WS luminaires can largely eliminate the unnecessary lighting of unoccupied cubicles while providing IESNA-required light levels when the cubicles are occupied. Because each cubicle's lighting is under occupant sensor control, the WS luminaires can capitalize on the fact cubicles are often unoccupied during normal working hours and reduce their energy use accordingly.

Introduction

Lighting systems consume about 25% of the electrical energy used in US commercial buildings (DOE 2007). Advanced lighting controls are the most practical means to dramatically reduce the energy footprint of commercial building lighting systems and to make building electrical systems more responsive to the real-time price of energy (NBI 2003). Despite these advantages, building owners, property managers and the energy efficiency community are largely unaware of how new control technologies have enhanced the capabilities of lighting systems. Intelligent, fully dimmable lighting fixtures are now commercially available that can be automatically or manually controlled to reduce energy use, improve demand response, and meet individual users' preferences.

The paper presents results from an investigation of new "workstation-specific" (WS) luminaires that are designed to provide highly efficient, customized lighting for cubicles in open-office areas. (Newsham et al. 2005) has examined the effectiveness of various task-ambient lighting systems in general, including occupant reactions. The field performance of WS luminaries specifically, has been best examined been examined in one, well-documented case study in British Columbia, Canada (Galasiu et al. 2007). That study investigated the energy savings and user acceptance in roughly 85 cubicles with one type of WS luminaire. In the current paper, we present the initial energy savings results from pilot studies of two different types of WS luminaires that are designed to provide highly efficient, customized lighting for cubicles in open-plan office areas. Lawrence Berkeley National Laboratory (LBNL) is working with the

General Services Administration (GSA) and Pacific Gas and Electric Company's (PG&E) *Advanced Technology Program for Federal Buildings* to test different WS luminaires in a series of small pilot studies at the Philip Burton Federal Building in San Francisco. The investigation presented in this paper is based on these pilots.

The U.S. General Services Administration is responsible for managing nearly 300 million square feet of commercial building stock in the U.S. Consequently, the GSA is in a position to examine the technical performance and cost-effectiveness of different energy efficiency technologies in their existing buildings as well as in newly constructed Federal buildings. Upgrading lighting systems is often identified as an important method for reducing the energy footprint of federal buildings and complying with ever-tightening Executive Orders.

Our hypothesis is that a well-controlled lighting system can provide IESNA-required light levels and maintain luminance distributions appropriate to the office context at lower overall energy cost than a low-energy uncontrolled system.

Methodology

In this project, the GSA led the effort (with PG&E technical support) and conducted pilot studies on small groups of individuals' cubicle lighting systems. The goal was to find out what worked before changing out the whole floor's lighting system and controls. Two different types of WS luminaires were selected and installed in 15 cubicles. Researchers compared the energy, demand and light levels from these two experimental lighting zones to a control ('base') zone with an uncontrolled, but low power, indirect/direct lighting system.

The experimental zones used WS luminaires, one per cubicle, while the Base zone used a long indirect/direct luminaire covering all the cubicles in the zone. *Workstation-specific luminaires* have the following features:

- Form Factor: Indirect/direct, pendant-hung luminaire.
- Separable control of "ambient" and "task" lighting components. Usually one lamp in the fixture provides the "ambient" or uplighting component, while another lamp (or two) is used to provide downwards-directed "task" lighting component.
- Occupancy sensors and photocells built directly into the body of the fixture as well as all associated control circuitry required to commission and operate the system.
- Networked together using physical cabling (0-10 VDC, DALI or RS-485-like).
- Use a PC to run control software and a microcontroller unit to implement a controls communication protocol to the lighting over the physical cabling.

Two types of WS luminaires were tested in the pilot studies:

E type luminaires (6 cubicles): Each E-type luminaire contains three 32 watt T-8 fluorescent lamps, horizontally-oriented with one single-lamp dimming ballast controlling the inboard lamp for the ambient uplight component, and a 2-lamp dimming ballast controlling the outboard lamps for the downwards directed "task" component.

G type luminaires (9 cubicles): Each G-type luminaire contains two 54 watt HO T-5 fluorescent lamps, "top-over-bottom" lamp orientation, with a single-lamp dimming ballast controlling the upper lamp for the ambient uplight component and another, independent, dimming ballast controlling the lower lamp.

For initial evaluation, the average daily lighting energy use from the above luminaires was compared to two control zone baselines as follows:

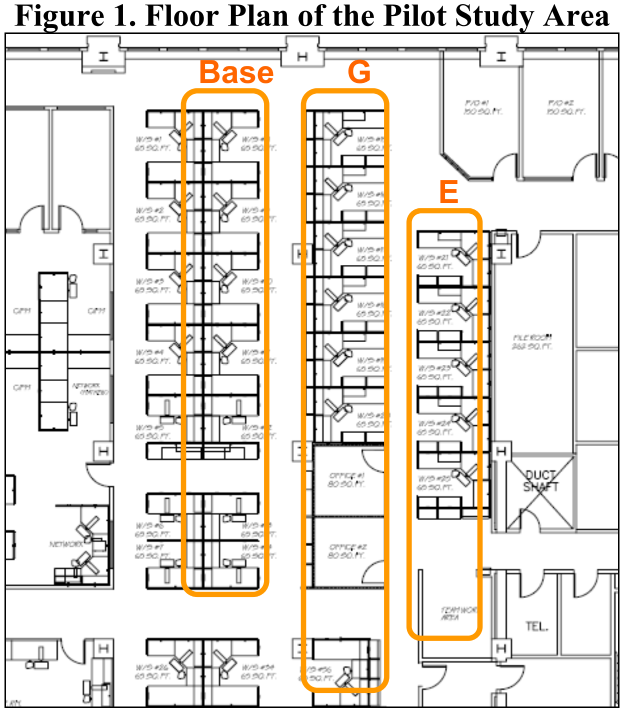
Base (7 cubicles): Pendant-hung, indirect/direct luminaires, 1-lamp cross-section. This lighting is one of the alternative lighting systems being considered for installation. Control is manual ON-OFF switching only from accessible wall switches. Lighting power density equals 0.88 watts/square foot.

Old Base: Recessed 2x4 18-cell "parabolic"-style. This is the building standard lighting, which is being gradually retired from service. Control is manual ON-OFF switching only. Lighting power density is 1.4 watts/square foot.

The advanced lighting fixtures being tested are designed to be pendant-mounted, and strategically located above each workstation in a typical open-plan cubicled office. Although WS luminaires have been criticized because of the difficulty of relocating the fixtures to accommodate changing cubicle layouts, GSA changes furniture arrangements sufficiently infrequently, that this is not thought to be a major detriment to system implementation.

The location and size of the two pilot experimental study zone areas are given in Figure 1 along with the location of the control Base zone.

Figure 1. Floor Plan of the Pilot Study Area



All the results reported in this paper are based on the electrical current measurements for the E and G test zones and the Base zone. Measurements were made using current transducers attached to the lighting switch circuits serving the cubicles for each zone. This report analyzed the data collected between September 19 and November 19, 2007. After eliminating bad data, this resulted in 19 working week days of "clean" data. (Because the installation of the E luminaires occurred several months after installation of the G luminaires, the above period was the only time when all systems were simultaneously working as intended). The measured electrical current values were converted to power assuming unity power factor. Because there are different numbers of cubicles in each circuit (6 cubicles with the E lights, 9 with the G and 7 with the Base system), we normalized the calculated power data to the number of cubicles (9) in the largest zone (G). These normalized measurements sum the power across all the cubicles in each zone and, by themselves, do not allow disaggregation of individual cubicle power usage. The nature of the collected data introduces some imprecision in the measurements. The current data was collected on 15-minute intervals, and each measurement is an instantaneous measurement of current, not an accumulated measurement over the last preceding 15-minute interval. In addition, a measurement of current is an imprecise measure of the total power because of the effect of power factor. However, by collecting sufficient data, researchers thought that the current measurements would be adequately precise to evaluate system operation during the pilot study. Complementary measurement techniques allowed researchers to record the approximate power on an individual ballast basis. The disaggregated data is not presented in this paper but will be presented in later publications.

Results

Energy Efficiency

A sample of 19 working weekdays (four work weeks) was selected for evaluation for the initial data analysis. Because there were minor operational differences between the 9 days between 10/9 – 10/19/2007 and the 10 days between 10/29 – 11/9/2007, the results are graphed (Figs. 2&3) separately for each of the two-week test periods. The average power usage on 15-minute intervals across the working day was computed and is shown in Figure 2 (10/9-10/19) and 3 (10/29-11/9). The measured energy use and savings over all 19 workdays of the test relative to the two Base cases is presented in Table 1.

Table 1. Energy Savings Calculations for the E and G Test Zones Relative to the Energy Used in the Base and Old Base Zones

	Lighting System			
	E	G	Base	Old Base
Actual Number of Cubicles per Zone	6	9	7	NA
Cubicle Size (Depth (ft) x Width (ft))	7 x 9	7 x 9	9 x 7	NA
Maximum Installed Lighting Power Density (w/sf)	1.38	1.74	0.88	1.4
Total kWh over 19 days, normalized to 9 cubicles (kWh)	444	1186	1021	1695
Normalized Average Daily Lighting Energy (kWh/day)	5.8	15.6	13.4	22.3
Average Daily Lighting Energy Intensity (Wh/sf)	10.3	27.5	23.7	39.3
Standard Deviation (Wh/sf)	2.89	5.51	1.66	NA
Projected Yearly Energy Intensity (kWh/sf/yr)	**2.9**	**7.7**	**6.6**	**11.0**
Energy Use Relative to Base	43%	116%	100%	166%
Energy Use Relative to Old Base	26%	70%	60%	100%
Energy Savings Relative to Base	**57%**	**-16%**	**0%**	**-66%**
Energy Savings Relative to Old Base	74%	30%	40%	0%

Figure 2. Lighting Power Densities for the E and G Test Zones and Base Zone. Averages and Standard Deviations Calculated over 9 Workdays (10/9 – 10/19/2007)

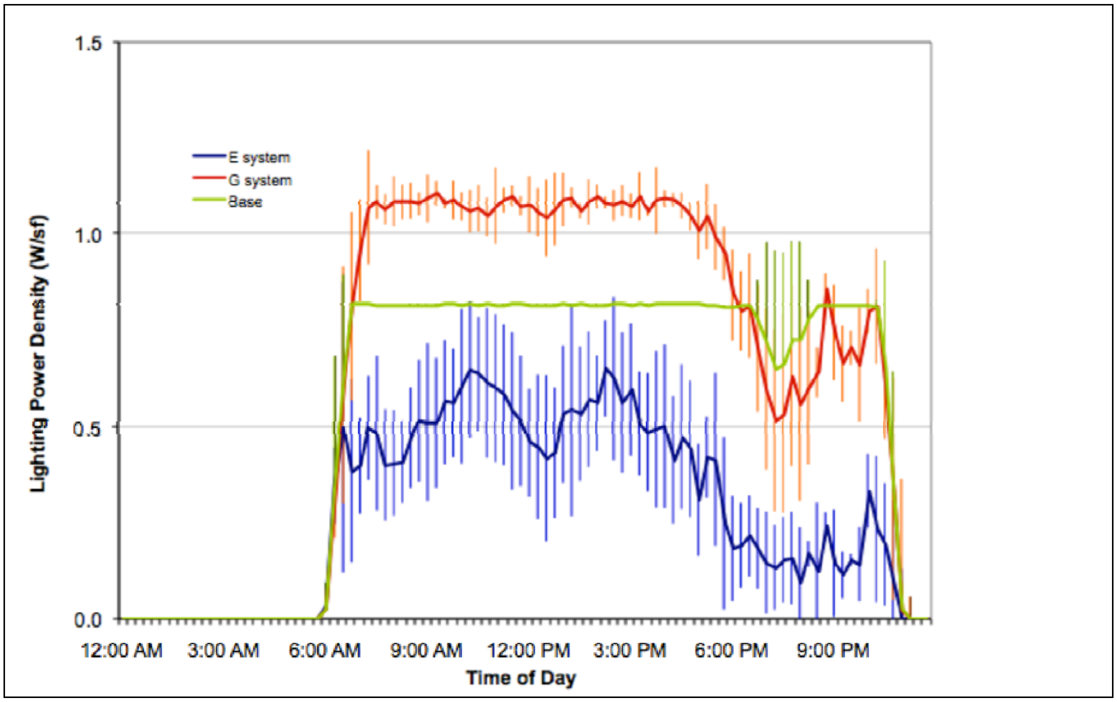
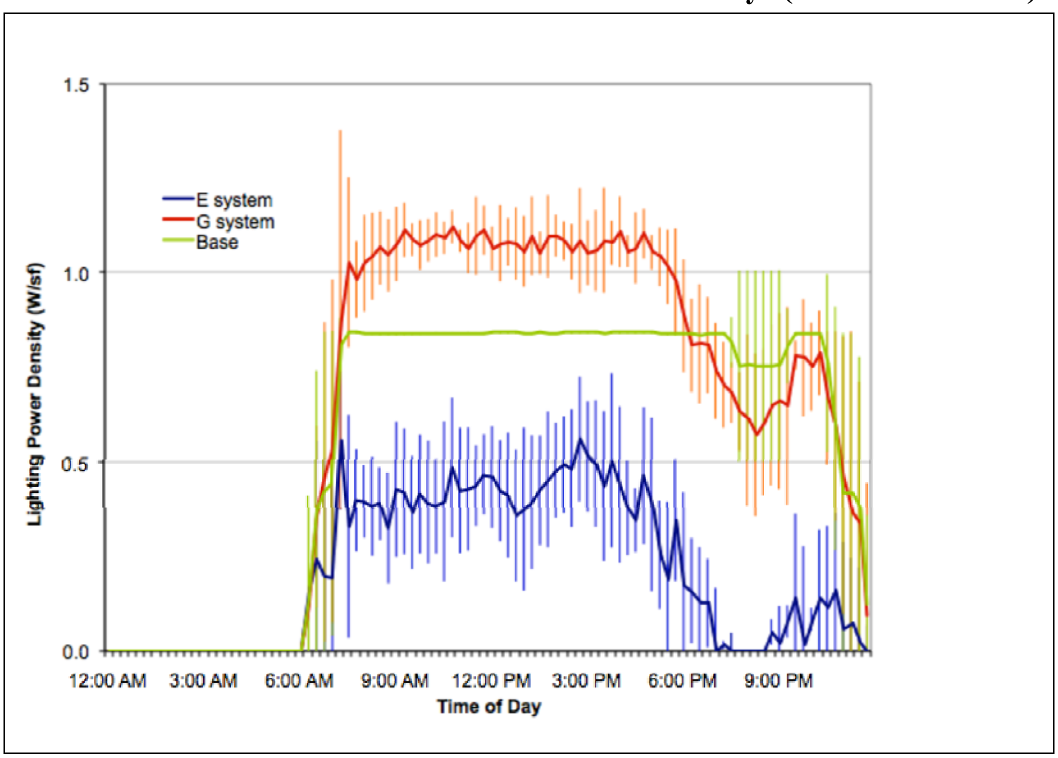


Figure 3. Lighting Power Densities for the E and G Test Zones and Base Zone. Averages and Standard Deviations Calculated over 10 Workdays (10/29 – 11/9/2007)



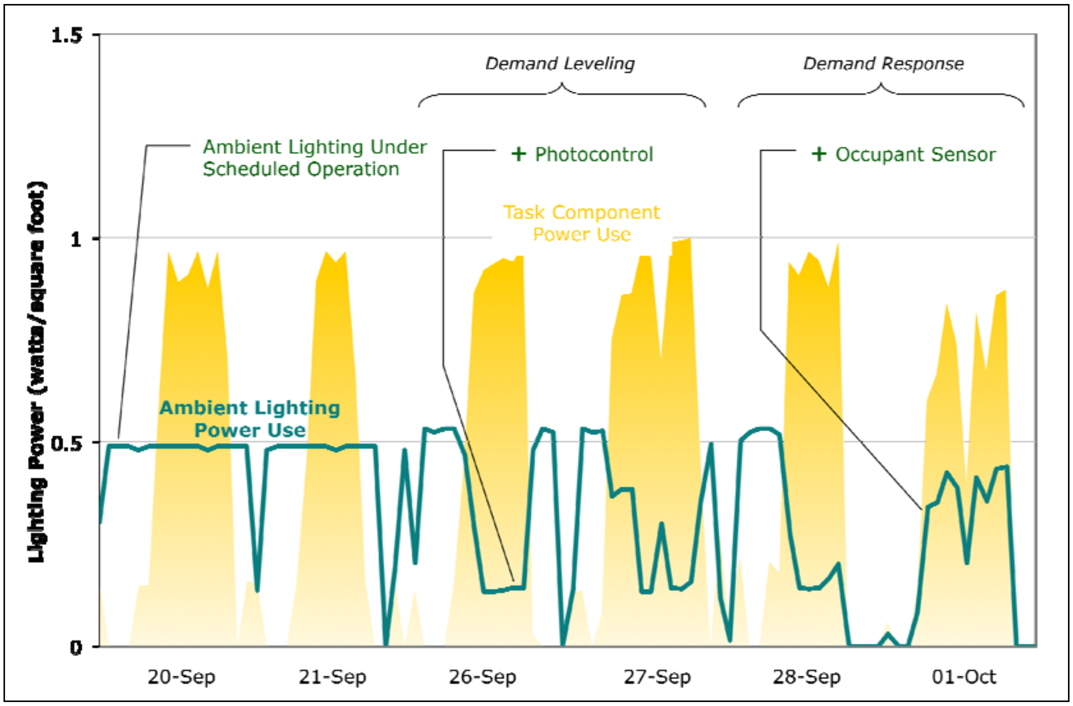
The E system is found to use only about half the power as the Base case during the main working hours (i.e., 8AM – 5PM) and lower levels still after regular working hours. This is due to the fact that the E system extinguishes the two outboard lamps after the cubicle is vacated, allowing the capturing of significant savings during the day. After hours, the usage is even lower closer to zero since the cubicles are consistently vacant then. The average daily use for the E system was only 10.3 Watt-hrs/sf, saving 57% relative to the Base case.

The G system, while similar control to the E system, was found have higher average daily use than the Base case (16%). It used more power than the Base case during main working hours and only dropped below the Base power levels after regular hours. As will be discussed in the following section, the occupancy sensors turned out to be the culprit. Methods to improve the performance of the G system were identified during the pilot study and remedies are proposed in the Discussion section.

Demand Response

Both demand response and demand leveling strategies were explored in this investigation. We show the results of one series of tests in which the system operator first implemented *demand leveling* (by placing the ambient lighting component (inboard lamp) under photocell control), and then *demand response* (by adding occupancy-sensor control). Prior to 26-Sep (Figure 4), the ambient lighting component was fixed at about 0.5 w/sf for 16 hours/day while the outboard lamps (task component) varied according to cubicle occupancy as determined by the luminaire's occupant sensor. For the Demand Leveling test (26-Sep and 27-Sep), the inboard lamp (ambient, uplight component) was placed under the luminaire's photocell control. In this low-energy mode, the inboard lamp dimmed whenever the outboard lamps were energized, saving energy, but came to full brightness whenever the cubicle was unoccupied to provide adequate light for adjacent areas. For the Demand Response test (starting 28-Sep) both the ambient and task components (all three lamps) were switched according the luminaire's occupant sensor. This simulated the lighting's response to a severe demand response event. The power drawn by the inboard lamp was significantly reduced during normal operating hours for both the demand leveling and demand response tests. During the demand response test, all lighting was entirely eliminated whenever the cubicle is unoccupied.

Figure 4. The Impact of Different Demand Response Techniques on the Ambient Lighting Power Use



When operating in the Demand Leveling or "normal" modes, the outboard lamps extinguish upon vacancy, but the single inboard lamp remains illuminated at a dimmed mode to provide some ambient lighting. The visual effect of this technique on lighting appearance is visible in Figure 5. In Figure 5, the two rightmost luminaires are at nominal "full light" level since the cubicles were recently occupied. The three left-most luminaires have both outboard lamps extinguished. Note the lower luminance above these fixtures.

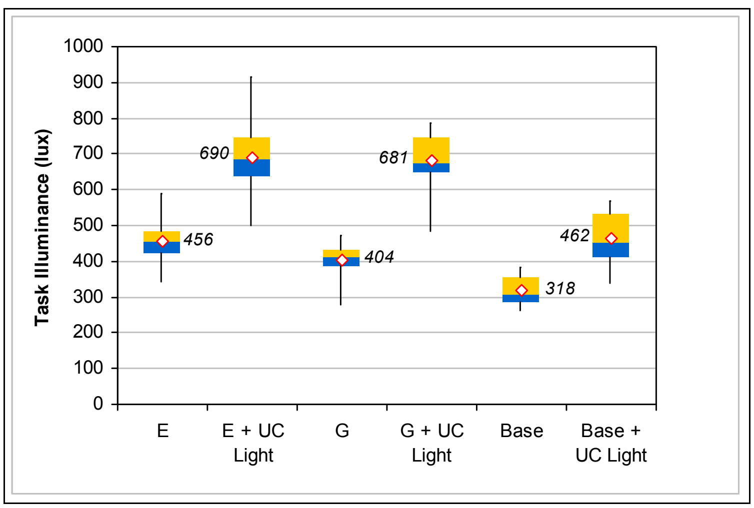
Figure 5. Effect of Demand Response on Quality of Lighting in E System Zone

However, the resultant spotty lighting during the more severe demand response test (not shown) indicated that occupancy-sensor switching of the ambient lighting might best be reserved for grid emergencies, which generally occur no more than about 100 hours a year. Researchers will employ imaging photometry at the site to photometrically document the effect of demand leveling and demand response strategies on the resultant lighting quality. (See (Newsham 2006) for research on the occupant acceptance of demand response strategies for lighting).

Light Levels

Light levels were measured in all 15 cubicles using handheld illuminance meters. Two measurement points were selected per cubicle, each at desk height and at the same position relative to the furniture system. Measurements were made with the overhead lighting only at nominal full output, and then repeated with all undercabinet fluorescent task lights in each cubicle switched on. The total undercabinet lighting power per cubicle varied between 45 - 50 watts/cubicle. All cubicles had two undercabinet lights, switchable by the occupants. Most of the lights were 1-lamp F20T12 (about 25 watts system power) with the remainder consuming around 20 watts.

Figure 6. Measured Light Levels in the Cubicles of the Two Test Zones (E and G) and Base Zone, Without and With Undercabinet Lighting



Light levels at desk surface were measured for each condition, with and without undercabinet lighting. Figure 6 shows a "box-and-whisker" plot for each condition: the mean, or average illuminance, is indicated by the small, red diamond. The distribution's second quartile is indicated in blue, the third quartile in yellow. The vertical "whiskers" indicate the data's total extent of the distribution. As shown in Figure 6, the E system provided on average around 455 lux in the six measured cubicles, the G system, 405 lux, and the Base system, about 320 lux. When each cubicle's undercabinet light is turned on, the light levels rise about 150 – 280 lux, but this also adds 45-50 watts to each cubicle's power burden.

Luminance Distribution

We performed imaging photometry on five cubicles to record and analyze the luminance distributions within the cubicles under different lighting conditions. Imaging photometry is thought to be useful for analyzing, for example, the luminance contrast ratios of key surfaces in the field of view – an important aspect of lighting quality as described by the IESNA (Rea 2000). The ratio between, say, the average luminance of the computer screen and the average of the immediate surround should not be more than 3:1 or less than 1:3. But when one examines images of real (messy) office spaces one quickly realizes that there are huge differences in average luminance simply due to the clutter of objects and surfaces in a typical office environment. As shown in the false color images below, the luminance variability simply to clutter in a messy office (Figure 7) makes it difficult to compare to a tidy office lit with a different lighting system (Figure 8). This analysis suggests that researchers will need to perform "before treatment" and "after treatment" lighting measurements in a sufficient sample of cubicles rather in order to understand the change in lighting quality due to lighting system and control strategy. A sufficiently large number of cubicles will be photometered before and after changing the overhead and task lighting systems to ensure that meaningful conclusions can be reached from the data.

Figure 7. False Color Map Showing Measured Luminance Distribution of Uncluttered Cubicle Lit with the Base Fixture

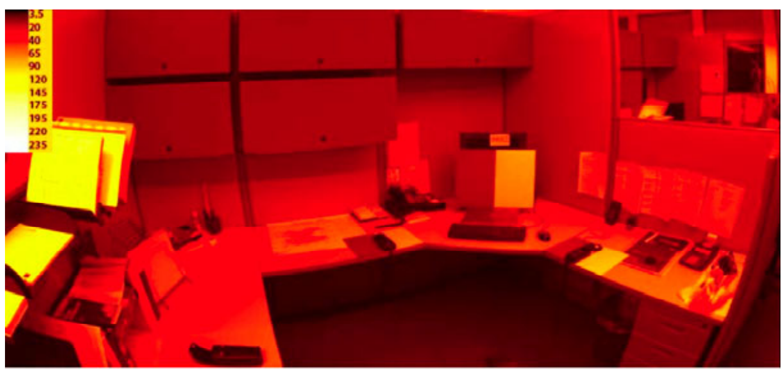
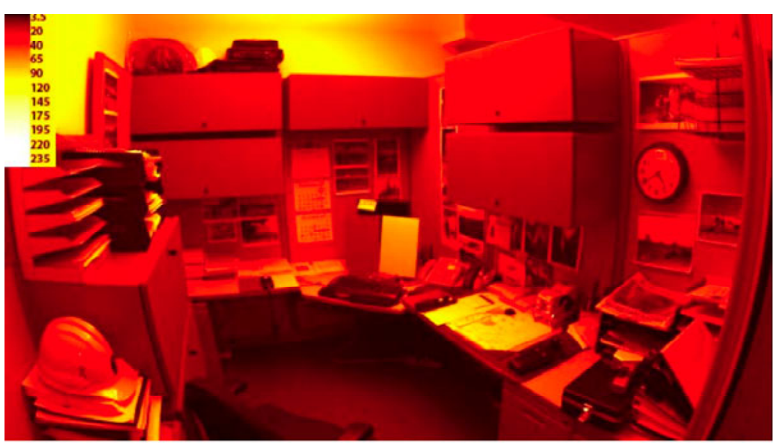


Figure 8. False Color Map Showing Measured Luminance Distribution of Cluttered Cubicle Lit with E Fixture



Discussion

The results showed that the E-type fixture provided appropriate IESNA light levels (Rea 2000) at the work surface and eliminated wasteful lighting of unoccupied cubicles. Most of the energy savings was obtained by the system dimming down and then extinguishing the lamps upon cubicle vacancy. Cubicle occupancy is frequently only around 50%; thus a system that can exploit this low occupancy rate can save a comparable amount. The energy savings found here are consistent with the results of (Galasiu et al. 2007), which also range around 50%. A well-placed and properly shielded occupancy sensor was key to achieving this high savings rate.

In contrast, the results showed that the G-type fixture did not turn off cubicle lighting when the cubicles were vacated, thus causing the lighting to be on most of the working day. Although the G fixture was somewhat dimmed, the failure to capture savings due to individual cubicle vacancy, and the lack of daylight in these spaces, meant that the G fixture was not saving energy as currently applied. Further investigation showed that all the deficiencies noted in the G-type fixture could be solved by the manufacturer making small modifications to the luminaire and control sensors. The most significant improvement in performance would be to replace their current occupancy sensor with another sensor that has a smaller field of view that would only cover cubicle occupancy and not false trigger. This would prevent the G luminaire from "false triggering" ON the cubicle lights because of adjacent corridor traffic. This one measure would greatly improve the performance of the G system for this cubicle application. Second, the manufacturer should use a lens or lens and louver for the downwards-lighting component in order to achieve better light coverage over the entire work surface. Finally, the maximum power density of the G system could be reduced to that of the E system by using a lower wattage T5 lamp (28 w) for the uplight while continuing to use a 54 T5 HO for the downlight component. We believe that if all these measures were put it in place, that the energy performance of the G system could be equivalent to the E system.

Based on the results from the pilot studies, GSA has decided to install workstation-specific lighting in one-half of the 4th floor of the Philip Burton Federal Building. This expanded demonstration will include approximately 80 cubicles. Some of the planned space is daylit, so this will provide an opportunity for the GSA to measure the impact of this important strategy as an energy and demand reduction measure. In addition to testing the selected WS luminaires' performance using different control strategies, the existing undercabinet fluorescent lighting will be replaced with modern T-4 microfluorescent lamps or LED task lights and undercabinet lamps. Task lighting power will be measured in the demonstration and "before" and "after" imaging photometry performed on an adequate sampling of workstations to quantify the changes in light level and distribution under different operating conditions.

Conclusion

The energy savings, demand response capabilities and quality of light from the two WS luminaires were evaluated and compared to the performance of a static, low-ambient lighting system that is uncontrolled. Initial results from several weeks of operation indicate that WS luminaires can eliminate the energy used to light unoccupied cubicles while providing IESNA-required light levels when the cubicles are occupied. Since each cubicle's lighting is under occupant sensor control, the WS luminaires can capitalize on the fact cubicles are often unoccupied during normal working hours and reduce their energy use accordingly. The measurements show that WS luminaires can provide a lower lighting energy footprint in cubicled spaces than a low-energy static system that is insensitive to cubicle occupancy and user requirements. Further, the lighting measurements showed that WS luminaires provided higher light levels over a significant portion of the task surface than an uncontrolled static system.

References

[DOE] Department of Energy. 2007. 2007 *Buildings Energy Data Book*, Table 1.3.3, http://buildingsdatabook.eren.doe.gov/.

[NBI] New Buildings Institute. 2003. *Advanced Lighting Guidelines 2003*, Table 8.4, http://www.newbuildings.org.

Galasiu, A.D., G.R. Newsham, C. Suvagau, and D.M. Sander. 2007. "Energy Saving Lighting Control Systems for Open-Plan Offices: a Field Study." *Leukos*, 4 (1).

Newsham, G., C. Arsenault, J. Veitch, A. Tosco, and C. Duval. 2005. "Task Lighting Effects on Office Worker Satisfaction and Performance, and Energy Efficiency", *Leukos*, 1 (4).

Newsham, G. and S. Mancini. 2006. "The Potential for Demand Responsive Lighting in Non-Daylit Offices", *Leukos*, 3 (2).

Rea, M., ed. 2000. *The Illuminating Engineering Society of North America Lighting Handbook. 9th edition.* New York.

Acknowledgements

This work described in this report was coordinated by the Demand Response Research Center and funded by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No. 500-03-026 and by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This work was also supported by the U.S. General Services Administration, Pacific Gas and Electric Company, Enovity, Inc. and Peter Schwartz and Associates, LLC.